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LIQUID TRANSFER DEMONSTRATION ON BOARD APOLLO 14 DURING TRANSEARTH COAST

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16. Abstract

The transfer of liquid from one container to another in a weightless environment was demonstrated by the crew of Apollo 14. A scale-model liquid-transfer system was used on board the spacecraft during the transearth coast period. The liquid transfer unit consisted of a surface tension baffled tank system containing two baffle designs. Liquid was transferred between tanks with a hand pump operated by the astronaut. The results showed that liquid was efficiently transferred to and from either baffled tank to within two percent of the design value residual liquid without reaching gas ingestion. The liquid-vapor interface in the receiver tank was positioned successfully with the gas located at the vent.

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SUMMARY

The transfer of liquid from one container to another in a weightless environment was demonstrated by the crew of Apollo 14 by using a scale model liquid transfer system on board the spacecraft during the transearth coast period. The liquid transfer unit consisted of a surface-tension baffled tank system containing two baffle designs and an unbaffled tank set for comparative purposes. When the unbaffled tank set was operated at a transfer rate which resulted in a stable interface during inflow to the receiver tank, gas ingestion in the supply tank occurred when less than 12 percent of the supply tank volume had been delivered. In addition, liquid was positioned at the vent side of the supply tank at initiation of transfer. At the termination of transfer, liquid had ingested in the receiver tank vent. For the baffled tank set operating at nominally the same transfer rate, liquid was transferred to and from either baffled tank to within 2 percent of the design-value residual liquid without reaching gas ingestion. The liquid-vapor interface in the receiver tank was positioned successfully with the gas located at the vent.

INTRODUCTION

One element of propellant management that will be necessary in future space operations will be that of liquid transfer from a tanker vehicle to a receiver vehicle. Examples are transfer of propellants from a shuttlecraft to space station tanks or to propellant tanks for vehicles designed for lunar or interplanetary missions or the transfer of vital fluids to the space station. Depending on the mission, the transfer process may be required to fulfill one to all of the following conditions:

(1) Gas-free outflow from the supply tank with a high total delivery efficiency

(2) Orderly inflow into the receiver tank with no liquid loss through the gas vent

(3) Ability to achieve a configuration with the gas located at the tank vent and the liquid at the drain/fill port.

(4) Ability to recover from or withstand acceleration perturbations.

A thorough knowledge of the outflow characteristics from the supply tank, subsequent fluid behavior during the filling of the receiver tank in a reduced gravity environment, and the effects of adverse accelerations on the liquid-vapor interface are required for the design of these transfer systems.

A considerable amount of experimentation and a limited amount of analytical work has been done in the areas of liquid draining and liquid inflow in reduced gravity. However, few results are available on the complete transfer of liquids for tank systems using surface tension principles in a weightless environment because of the short times available in ground based facilities. The experiments that have been performed were restricted to specific studies of individual problem areas directly related to liquid transfer. Some of these include draining phenomena from partially filled containers in reduced gravity (refs. 1 to 7), liquid inflow to tanks in weightlessness (refs. 8 to 11), studies of the retention characteristics for surface tension screens and baffles (refs. 12 to 22), and outflow and inflow studies with screens or baffles (refs. 1 and 23 to 27). Each of the experimental studies added to the state-of-the-art design capabilities for complete liquid-transfer systems. The analytical works performed (such as refs. 28 to 36) did not provide solutions to the complete transfer process in reduced gravity. Rather, they resulted in order-of-magnitude tradeoff comparisons for a variety of liquid-transfer schemes, or they were limited to analyses of the outflow or draining phenomenon.

The single significant conclusion that could be drawn from the collective contributions of all these works and other uncited studies related to liquid transfer was that liquid-transfer systems with high total-delivery efficiency could not be achieved in weightlessness without the addition of internal devices to control the position of the liquid-vapor interface.

The purpose of this study was to demonstrate the effectiveness of two surface-tension baffle designs to satisfy the first three conditions mentioned earlier. The baffle designs combined the desirable characteristics of existing baffle and screen concepts into an integrated scale-model liquid-transfer system. This was a self-contained closed system containing a pair of baffled tanks. In addition, a second pair of similar but unbaffled tanks was tested for comparative purposes. The demonstration apparatus was carried on board Apollo 14 with the astronauts performing the test operations during the transearth coast period.

APPARATUS

The liquid-transfer demonstration apparatus consisted of a tank assembly unit, a hand-operated piston pump, and interconnecting flexible tubing, as shown in figure 1(a). The tank assembly unit contained two separate sets of model tanks arranged back-to-back and separated by a lighting frame. One pair of tanks was designed with internal surface tension baffles; the second pair had no devices whatsoever. The tank assembly unit components are shown in the photograph in figure 1(b). The baffled tank section is shown in exploded view and the plain tank section is illustrated mounted to one side of the lighting frame.

Each tank section was an integral subassembly, consisting of a frame, cover sheets, valves, and, as applicable, baffles. The tanks were flat cylinders designed to simulate in two dimensions the three-dimensional flow in a spherical tank. The two-dimensional design was more amenable to photographic fluid flow analysis. These tanks were 10.16 centimeters (4.0 in.) in diameter, and the flat faces were separated by 0.635 centimeters (0.25 in.). Each tank contained two ports, representing drain/fill and vent lines 0.48 centimeter (0.19 in.) in diameter and were positioned 180° apart. The drain/fill ports on each pair of tanks were connected by a transfer tube that contained a slide-action isolation valve. The vent port on each tank contained an identical slide-action valve. The tank cover sheets were clear plastic for photographic purposes. In addition, the external plastic surfaces that faced the lighting frame section were frosted to provide diffuse illumination. Furthermore, all external plastic surfaces were covered with laminated safety glass and an overlay of thin fluoroplastic sheet to ensure maximum crew safety. The lighting frame contained six incandescent lamps utilizing spacecraft power. These lamps provided the necessary illumination for photographic purposes.

The hand-operated piston pump, shown in detail in figure 1(c), is a screw-driven piston providing a positive pressure on one side while creating a suction on the other side. The pump can be operated in either direction. The tubing, sized for a friction fit over pump and tank port connections, could be easily switched to permit pumping between the baffled tank set or between the plain tank set.

The liquid used in the tanks was an inert fluorochemical, perfluorotributylamine, which satisfied the safety requirements for the spacecraft. Furthermore, the liquid had a near zero degree static contact angle on the tank surfaces to simulate the contact angle of most propellants on typical spacecraft materials. To improve the quality of the photographic data, a small amount of dye was added to the liquid. Addition of this dye had no measurable effect on the liquid properties. The values of density and surface tension for the dyed liquid measured at 20° C were 1.9 grams per cubic centimeter and 16.7×10^{-5} newtons per centimeter (16.7 dyn/cm), respectively.

OPERATING PROCEDURES AND DATA RECOVERY

The complete liquid-transfer system was designed to allow maximum flexibility during operation while maintaining simplicity and a minimum of mechanical and electrical interfaces with the spacecraft. All mechanical functions of the system were hand-operated by the crew. The only electrical interface was the backlighting of the tanks. During transfer operations, one crew member photographed the tanks either with a motion picture sequence camera or with the onboard video camera, while another operated the piston pump at a prescribed rate.

Each tank set section, when connected to the piston pump with the flexible tubing, makes up a closed-loop liquid transfer system. One of the tanks, starting with a predominantly liquid filled condition, represents the supply tank. The other tank in the set, either empty or nearly empty, is the receiver tank. The "vent" sides of both tanks were connected to the pressure and suction sides of the pump, respectively, closing the system. The isolation valves on the vent side are opened, as well as those on the transfer tube valve interconnecting the "drain/fill" side of the tanks. Operation of the hand-crank on the piston pump in one direction pressurizes the supply tank and simultaneously creates an equivalent amount of suction in the receiver tank causing fluid flow. By rotating the crank uniformly the flow rate remains reasonably constant. Transfer is continued until (1) liquid is depleted from the supply tank, (2) vapor is beginning to ingest into the outlet of the supply tank, or (3) liquid reaches the vicinity of the vent side of the receiver tank. On completion of a transfer operation liquid transfer can be reversed simply by rotation of the pump in the opposite direction. The receiver tank, which is now relatively full of liquid, becomes the supply tank.

The film records for these operations yield data indicating the amount of liquid transferred, flow rates, and interface configurations. This is accomplished by transcribing the interface configuration to a scale drawing of the tank cross section. By mapping this transcription the volume of liquid in the tank for this instant in time can be estimated. Iteration of this process over the transfer time resulted in reasonable estimates of values for flow rate and amounts of liquid transferred.

The test conditions during the period of performance of liquid-transfer operations by the astronauts, as received from the spacecraft, were values of cabin pressure of 3.54×10^{-4} newton per square meter (5.135 psia) and cabin temperature of 297.0±0.3 K (74.9±0.5° F). Continuous readout of the spacecraft attitude for all three axes of rotation indicated that the vehicle motion ranged between 4° and 12° per hour depending on the axis. As a result, the gravitational effects on the liquid-transfer system were negligible and the system was considered to be in weightlessness.

SURFACE TENSION BAFFLE DESIGNS

Two surface-tension baffle configurations were used in this liquid-transfer demonstration. Each was designed to achieve the following objectives:

(1) Gas-free outflow from the supply tank with a high total delivery efficiency

(2) Orderly inflow into the receiver tank with no liquid loss through the gas vent

(3) Ability to achieve a configuration with the gas located at the tank vent and the liquid at the drain/fill port.

The details of the resulting baffle designs are shown in figure 2. The tanks with their respective baffle geometries are designated standpipe-liner and curved-web for descriptive purposes.

Standpipe-Liner Baffle Design

The standpipe-liner baffle design consists of a perforated standpipe located over the drain/fill port and a wall-liner spaced, as shown in figure 2(b), a fixed distance away from the tank wall. The standpipe has the characteristics of a capillary tube and will retain liquid within the standpipe and externally adjacent to the standpipe. The standpipe tank has been demonstrated to be very effective in positioning the liquid in the tank area about the standpipe base, even when the liquid is initially adversely located and also under limited acceleration perturbations (refs. 12, 13, 15, 16, 37, and 38). The wall-liner is a capillary surface which locates a layer of liquid along the tank wall. The spacing of the liner away from the tank wall and the hole size of the openings in the liner determine the inherent residual liquid remaining after draining. The liner concept has been shown to be effective for expulsion tanks (refs. 4, 14, and 19 to 22). The combined effects of these two concepts results in a capillary system that has the characteristics of retaining liquid in a preferential location and permitting liquid flow in or out from the same location. In order to prevent premature vapor ingestion through the standpipe during draining, a solid deflection baffle was placed at the base of the standpipe. In addition, the incoming pressurant is diffused by deflecting the flow 90°. The location of this pressurant inlet port is extended within the tank such that it is located in the center of the anticipated ullage space in weightlessness when the tank is 90 percent full of liquid. A photograph of this equilibrium configuration in a weightless environment is shown in figure 2(c). This photograph was taken from a test drop at the Lewis Research Center's 5- to 10-Second Zero Gravity Facility.

Intrinsic to the wall-liner design is the fact that the volume of liquid contained between the screen liner and tank wall is considered residual liquid. This volume is considered nondeliverable for outflow applications because once the inner tank liquid content has been drained, vapor ingestion can occur unpredictably anywhere along the screen.

The wall liner for this design and model size contains 10 percent of the tank volume. This design penalty in full sized tanks can be on the order of 1 percent of the tank volume.

Curved-Web Baffle Design

The curved-web baffle design consists of a series of three circular perforated plates nested around a small feeder capillary section (as shown also in fig. 2(b)). The circular-shaped plates, or curved-web baffles, are arranged off-center such that the cross-sectional area between baffles increases gradually from the feeder capillary section towards the opposite end of the tank. This arrangement tends to locate the liquid-vapor interface such that the liquid bulk is adjacent to the feeder capillary. As in the standpipe-liner tank, the curved-web baffle system also contains both a small deflection baffle over the feeder capillary section and a pressurant gas diffuser. A photograph of the equilibrium configuration in a weightless environment for the curved-web design is shown in figure 2(d).

The feeder capillary section used in this baffle design also represents a built-in residual liquid or nondeliverable liquid volume. In this case the feeder capillary contains 1 percent of the tank volume. The design penalty in full sized tanks can be on the order of 0.1 percent of the tank volume.

RESULTS AND DISCUSSION

The efficient transfer of liquid from one tank to another in a weightless environment is primarily dependent on the initial liquid-vapor interface shapes, their positions in both the supply and receiver tanks, and the flow rate during transfer. In preparation for the scheduled test program and during operations to familiarize crew members with techniques in the weightless environment, small amounts of the liquid inadvertently became trapped in the piston pump system. As a result, the initial fillings for the tests varied, although this should not detract from the performance demonstration of the system operation. Several transfer operations were performed by the crew. The results of four of these tests have been selected as representative of the system operation. Three of the tests are for the baffled tank system; the fourth, for an unbaffled tank test, is included for comparison.

Liquid Transfer with Unbaffled Tanks

The results of a liquid-transfer operation with unbaffled tanks are presented in a photographic sequence in figure 3 (camera was not perpendicular to tank face). Adjacent to each photograph is a sketch of the shape of the liquid-vapor interface shown in the photograph. When considering the tank geometry, wetting characteristics of the test liquid, and the weightless environment, the interface is expected to be circular in shape, forming a gas bubble randomly located within the tank (refs. 39 and 40). Indeed, the configuration at the initiation of liquid transfer (fig. 3(a)) consisted of a circular-shaped vapor bubble in the supply tank located such that a liquid layer covered both the drain and vent sides of the tank. The liquid filling is estimated to be 36 percent of the tank volume, with an additional 10 percent contained in the transfer tube connecting the two tanks. A gas bubble formed directly over the vent or pressurant inlet as the tank was pressurized to start the transfer.

During transfer (see fig. 3(b)), the liquid-vapor interface in the receiver tank was deformed because of the incoming liquid jet; however, the interface appeared stable. The stability of the interface during liquid inflow is a function of the liquid-jet velocity (ref. 8) and, therefore, the flow rate. The liquid-jet velocity was used in reference 8 in obtaining an inflow Weber number which predicted the stability of the interface during inflow in weightlessness. Using the flow rate, which was estimated to be 0.8 cubic centimeter per second for this transfer test, the inflow Weber number was calculated to be 0.27, which is well within the critical value of 1.3 stated in reference 8, and, therefore, predicts stable inflow.

The inception of gas ingestion from the supply tank into the transfer tube is shown in figure 3(c). Gas ingestion occurred quickly at a point where the liquid remaining was 24 percent of the tank volume, which for this case resulted in less than 12 percent of the tank volume being delivered. The transfer operation was continued as shown in the remainder of the photographic sequence with frames illustrating bubble entrainment and growth in the receiver tank. As expected, liquid eventually ingested in the receiver tank vent.

Liquid Transfer with Baffled Tanks

The results for three liquid-transfer operations performed with surface tension baffled tanks are presented in this report. The first of these transfer tests used the curved-web baffled tank as the supply tank and the standpipe-liner as the receiver tank. The second test reversed the procedure with the standpipe-liner as the supply tank. For these tests, the flow rate was the same order of magnitude as for transfer with the unbaffled tanks. The third transfer operation was performed at about four times the flow rate with the curved-web tank as the supply and liquid flow to the standpipe-liner tank receiver. Selected photographs from each test are presented in figures 4 to 6 respectively, with sketches of each photograph for clarification.

Liquid transfer from the curved-web supply tank to the standpipe-liner receiver tank at an estimated flow rate of 0.83 cubic centimeter per second is illustrated in figure 4. The initial configuration (fig. 4(a)) indicates the retention characteristic of the curved-web baffle with the tank filled to about 64 percent of the tank volume. The bulk of the liquid is positioned over the drain side of the tank with the gas or ullage surrounding the vent. The wall-liner of the standpipe-liner receiver tank is nearly filled with liquid. As the transfer operation progresses, the liquid-vapor interface in the supply tank recedes in an orderly fashion down to the point of incipient gas or vapor ingestion (fig. 4(f)). During the same time, the receiver tank fills in an orderly manner also, with liquid filling the standpipe last. With the exception of a small amount of liquid in the capillary tube above the drain, nearly all the liquid in the supply tank was delivered to the receiver without gas ingestion from the supply tank and without liquid loss through the vent of the receiver tank, thereby clearly and successfully demonstrating the three design objectives.

Liquid transfer from the standpipe-liner supply tank to the curved-web receiver tank at an estimated flow rate of 0.67 cubic centimeter per second is illustrated in figure 5. The initial configuration in the supply tank (fig. 5(a)) is shown for an estimated volume fraction of liquid of 79 percent with the gas bubble retained between the standpipe and the vent tube. The receiver tank is completely empty. In succeeding sections of the figure, the interface shapes during the transfer test are shown. As liquid drains from the supply tank, the standpipe empties first, with the space between the standpipe and the liner draining next. The annular volume between the liner and the tank wall for this application is designed to remain full of liquid at the termination of transfer. This represents the residual liquid inherent to this design, since, as indicated previously, continuation of draining would result in an unpredictable vapor penetration anywhere along the wall liner, trapping liquid in the annulus. As shown in the figure 5(f) nearly all the supply tank liquid, with the exception of the liquid within the wall liner, was emptied without gas ingestion. During the filling of the receiver tank, the curved-web baffle controlled the interface position with no liquid loss through the gas vent. Utilization of the standpipe-liner tank as the supply and the curved-web tank as the receiver also demonstrated the orderly and efficient transfer of liquid in a weightless environment using surface tension baffles.

The transfer of liquid from the curved-web supply tank to the standpipe-liner receiver tank at a flow rate of 3.5 cubic centimeters per second is illustrated in figure 6. The initial configuration is shown in part (a) for a volume fraction of 59 percent in the supply tank. The receiver tank wall-liner is full before initiation of flow. Again, during transfer, the interface in both tanks is stable and moves in an orderly fashion. At this higher flow, however, some differences occur that are interesting to note. In the supply tank, the volume between the outermost web and the tank wall was the last to drain. These differences were attributed to variations in the dynamic pressure losses among the web channels. This indicates that the spacing of the webs and their perforations can be optimized by readjustment to provide uniform draining between webs. In this case, however, transfer was terminated when the interface for the inner webs reached the capillary tube over the drain (see fig. 6(f)) leaving a somewhat larger residual than for the transfer cases at lower flow rates. Similarly, the filling of the standpipe in the receiver tank lagged behind the filling of the rest of the tank, even more noticeably than for the transfer operation shown in figure 4. However, unlike that transfer, the standpipe did not fill completely even at the end of transfer (fig. 6(f)). This also indicates that the standpipe could be optimized by redesigning the spacing and perforations in order to improve the tank performance characteristics.

Estimated Liquid Fractions

The photographic data for the three liquid-transfer tests presented in figures 4 to 6 were used to calculate estimates of the liquid fractions from which a measure of the relative merits of the transfer operations could be obtained. The liquid fractions, which are ratios of the liquid volume to the tank volume, are shown in figure 7 for the three tests as a function of the transfer time. For each test the draining curve for the supply tank and the filling curve for the receiver are plotted. For each curve a straight line portion was drawn. These lines represent the average constant flow rate approximated for each test. The draining curve for the high flow rate test shown in figure 7(c) indicates that the pump was operated for nearly 4 seconds at a lower flow rate before the higher constant rate of 3.5 cubic centimeters per second was reached.

The test parameters and the liquid fractions for all the transfer tests including the test with the unbaffled tank are summarized in table I. The liquid fraction at the time of outflow termination, listed in the table as residual liquid fraction, ranged in values between 0.03 and 0.13 for the baffled tanks and was 0.24 for the unbaffled tanks. For the liquid-transfer test with the curved-web supply tank and standpipe-liner receiver tank operating at a flow rate of 0.83 cubic centimeter per second, the residual liquid was 3 percent of the tank volume. This compares favorably with the nondeliverable residual of 1 percent of the tank volume inherent to the feeder capillary section as discussed earlier in describing the baffle designs. The residual liquid for the reverse direction transfer test at 0.67 cubic centimeter per second was 13 percent of the tank volume, which also compares favorably with the design penalty of 10 percent for this baffle configuration. For the transfer test at 3.5 cubic centimeter per second using the curved-web tank as supply, the residual was 10 percent as compared with the 1-percent design penalty. In

TABLE I. - SUMMARY OF TEST PARAMETERS AND LIQUID FRACTIONS

Liquid-transfer configuration (supply tank to receiver tank)	Transfer flow rate, cc/sec	Initial liquid fraction (a)	Nondeliverable liquid fraction (design penalty) (a)	Measured residual liquid fraction (data) (a)
Unbaffled	0.80	0.36	(b)	>0.24
Standpipe-liner to curved-web	.67	.79	0.10	.13
Curved-web to standpipe-liner	.83	.64	.01	.03
Curved-web to standpipe-liner	3.5	.59	.01	.10

[a]All liquid fractions are ratios of supply tank total volume.
[b]Not applicable.

all cases for the baffled tank tests, the residuals were conservative, since the transfer operation was terminated before gas ingestion occurred.

CONCLUDING REMARKS

The transfer of liquid from one tank to another in a weightless environment was demonstrated by the crew of Apollo 14 by using an integrated scale-model liquid-transfer system on board the spacecraft during the transearth coast period. Two surface-tension baffle designs incorporated in separate tanks were shown to be effective both as supply tanks and as receiver tanks. Liquid was transferred to and from either baffled tank in weightlessness to within 2 percent of the nondeliverable liquid fraction (design penalty) without reaching gas ingestion. The liquid interface in the receiver tank was positioned successfully during inflow, with the gas at the vent.

Test results for transfer between two similar, but unbaffled tanks included for comparison, indicated, as anticipated, that unbaffled tanks were not suitable for transfer of liquid in weightlessness. Gas ingestion occurred when less than 12 percent of the supply tank volume had been delivered. In addition, liquid was positioned over the vent tube in the supply tank at initiation of transfer; and, at the termination of transfer, liquid had ingested in the receiver tank vent.

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National Aeronautics and Space Administration,
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113-31.

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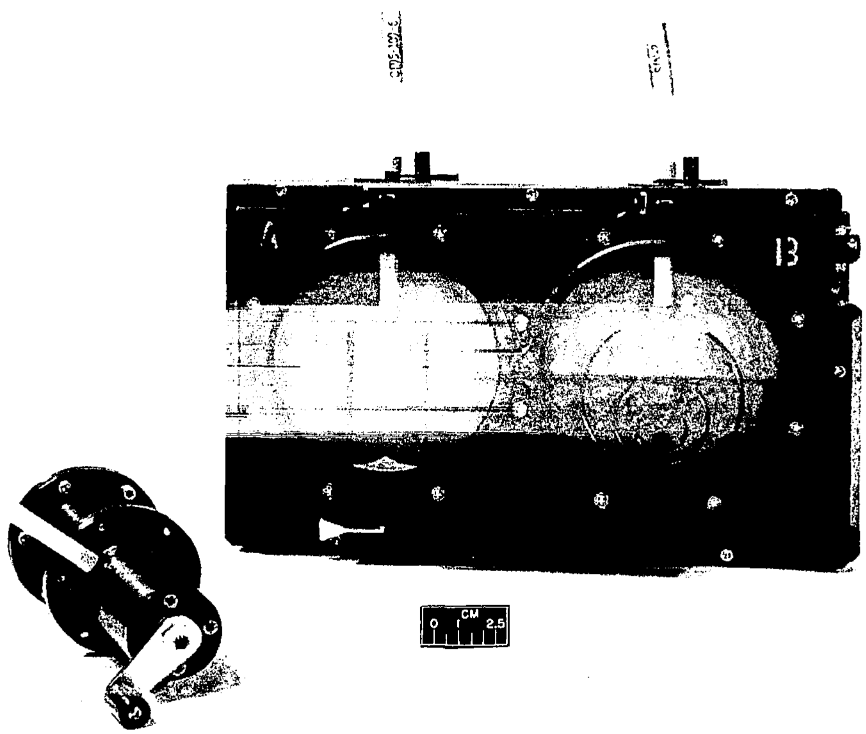

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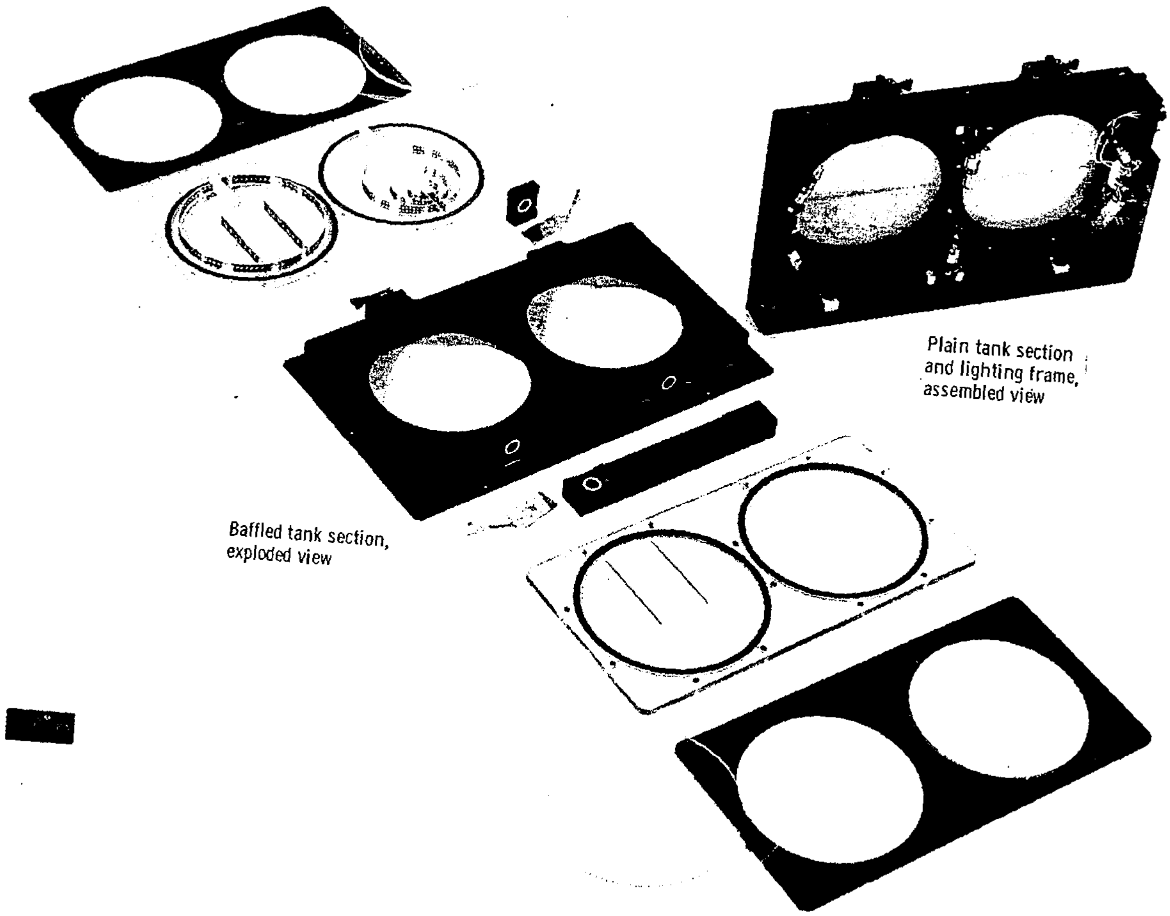
(a) Complete assembly showing flexible tubing connected from pump to baffled tank side.

Figure 1. - Liquid-transfer demonstration apparatus.



(b) Tank assembly unit components.

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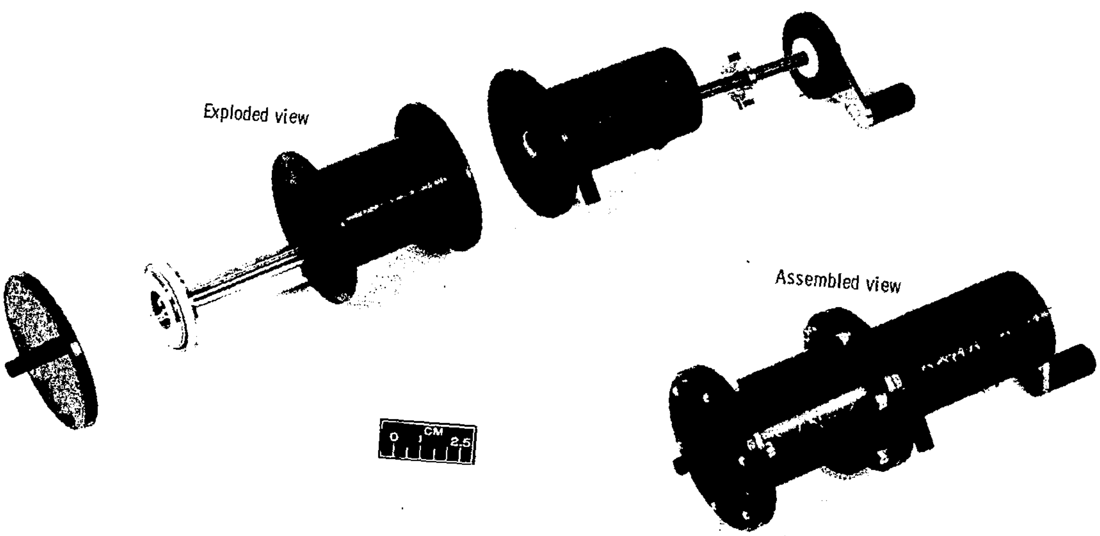

(c) Hand operated piston pump.

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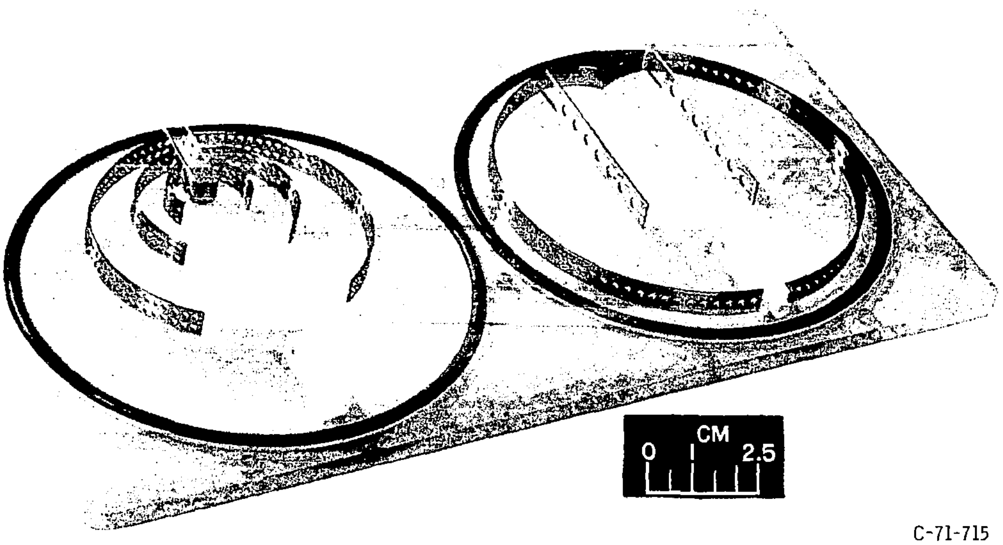
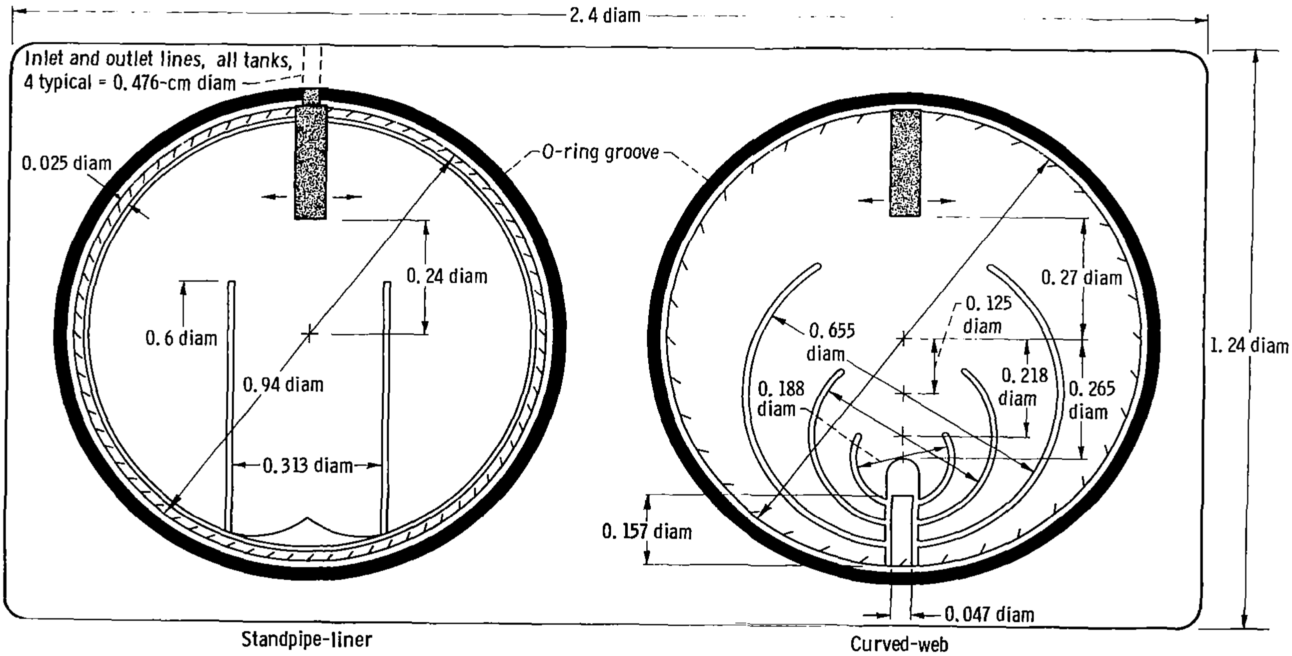
Figure 1. - Concluded.

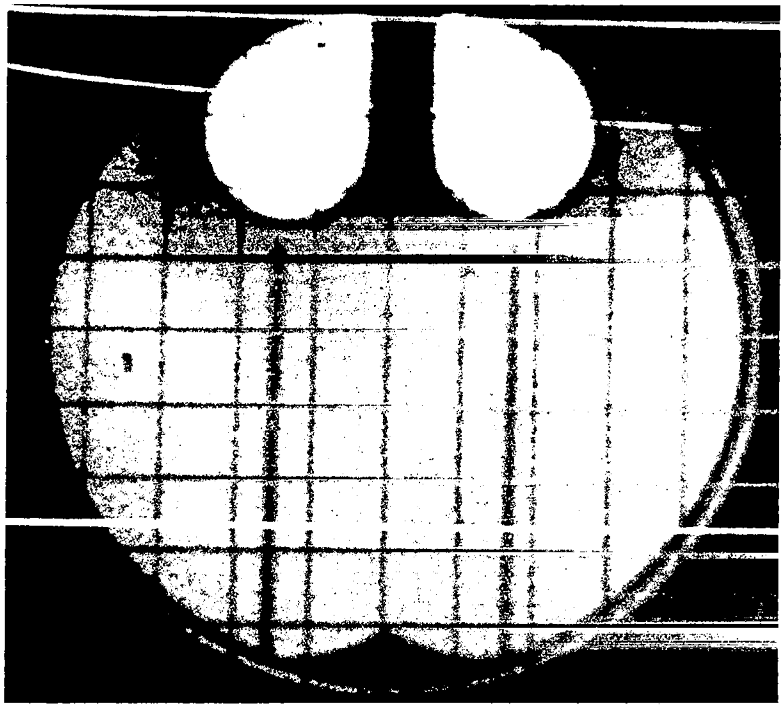


(a) Layout in baffle face plate.

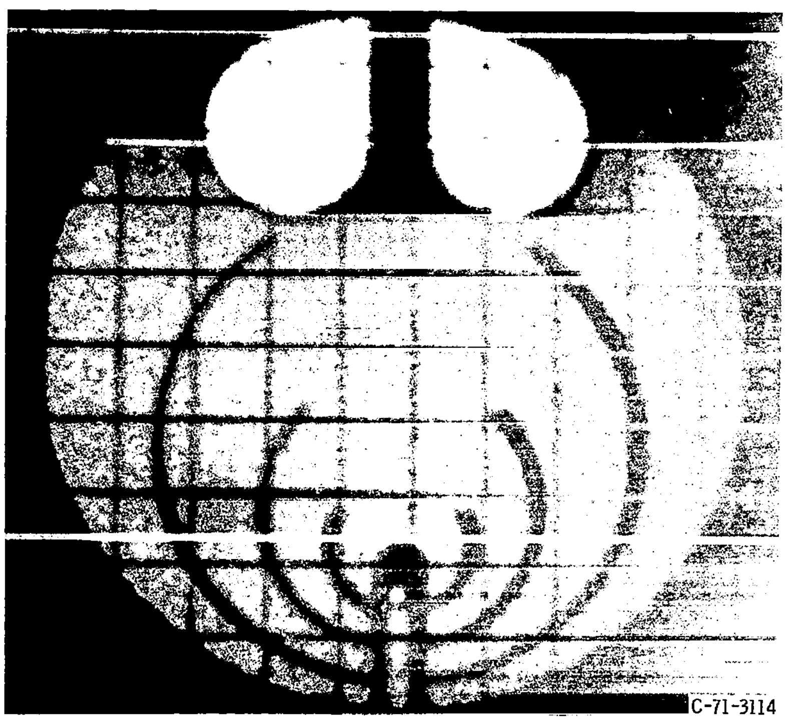


(b) Dimension details of baffles in face plate. All dimensions ratioed to tank wall reference diameter, (10.16 cm, 4.0 in.).

Figure 2. - Surface tension baffle designs.

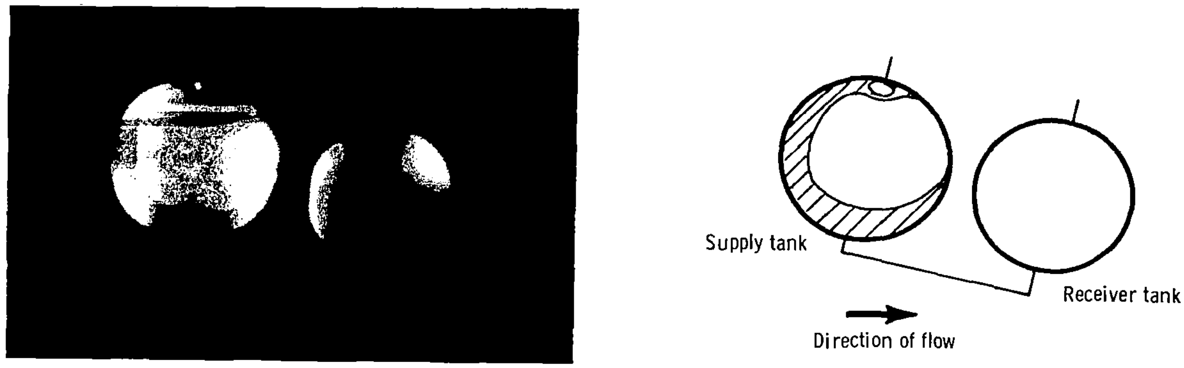


(c) Equilibrium liquid-vapor interface configuration in weightlessness for the standpipe-liner surface-tension baffle design.

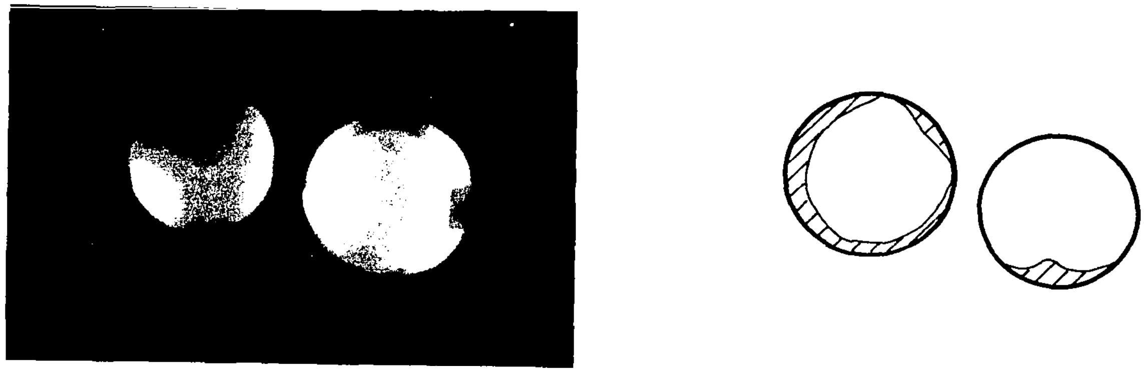


(d) Equilibrium liquid-vapor interface configuration in weightlessness for the curved-web surface-tension baffle design.

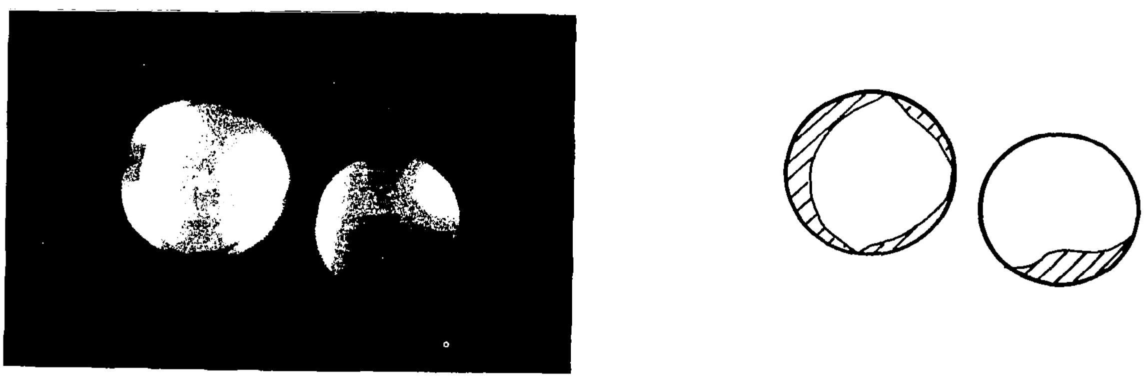
Figure 2. - Concluded.



(a) Initial configuration at initiation of liquid transfer.

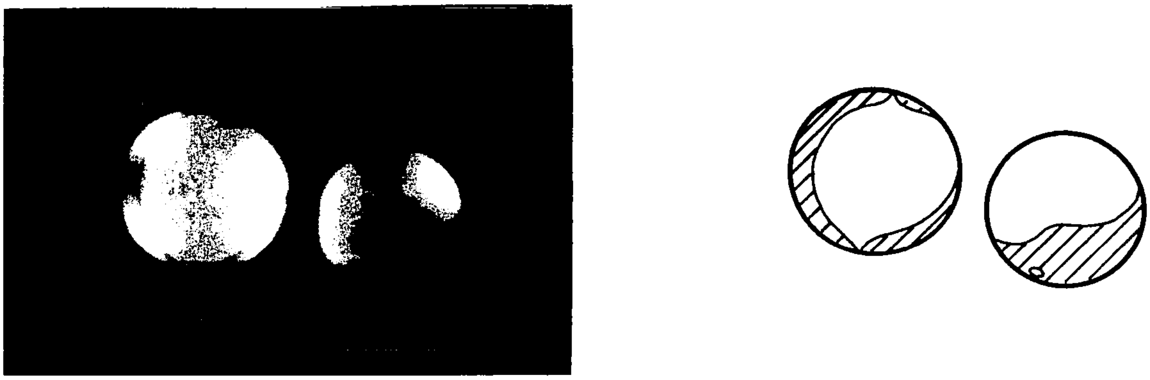


(b) Interface shapes during transfer; time interval, 5 seconds.



(c) Gas ingestion from supply tank; time interval, 7.3 seconds.

Figure 3. - Photographic sequence illustrating liquid-transfer phenomenon in plain, spherically shaped tanks during transearth coast. Approximate flow rate, 0.8 cubic centimeters per second.

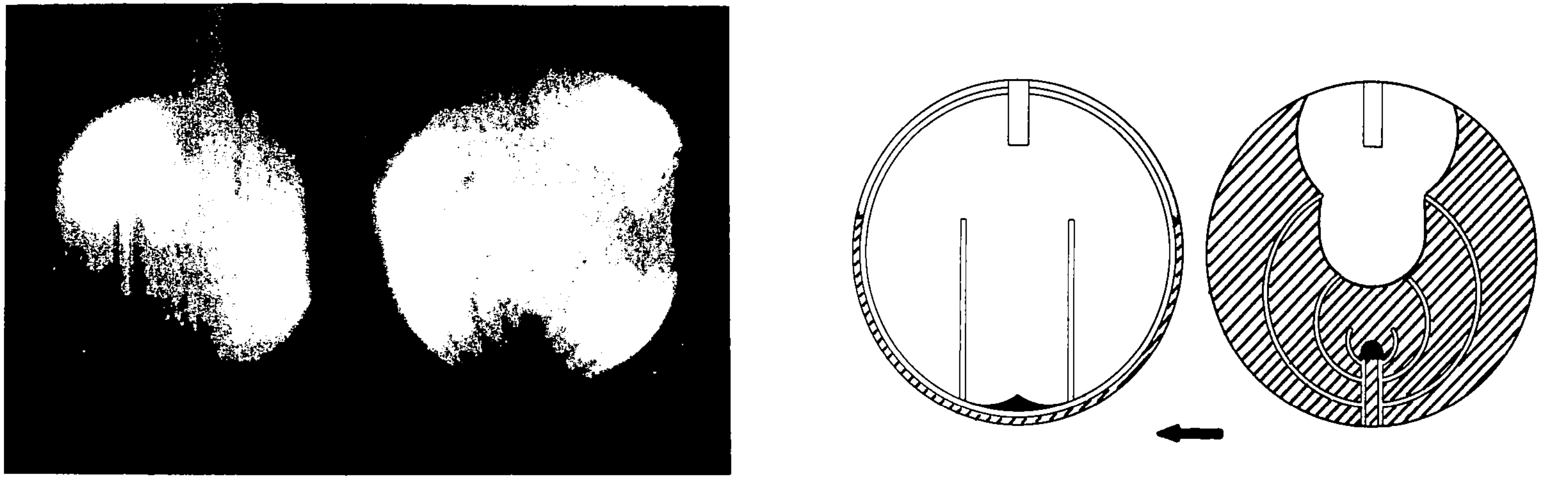


(d) Bubble entrainment in receiver tank; time interval, 13.3 seconds.

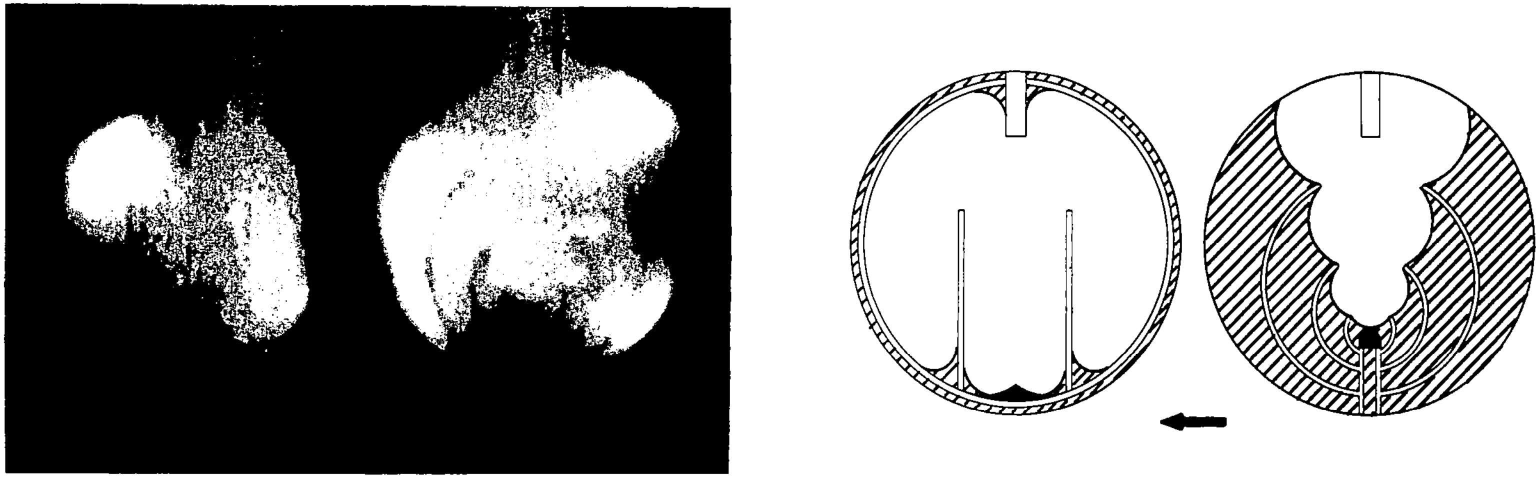
(e) Bubble growth in receiver tank; time interval, 17.8 seconds.

(f) Liquid ingestion in receiver tank vent; time interval, 27.8 seconds.

Figure 3. - Concluded.

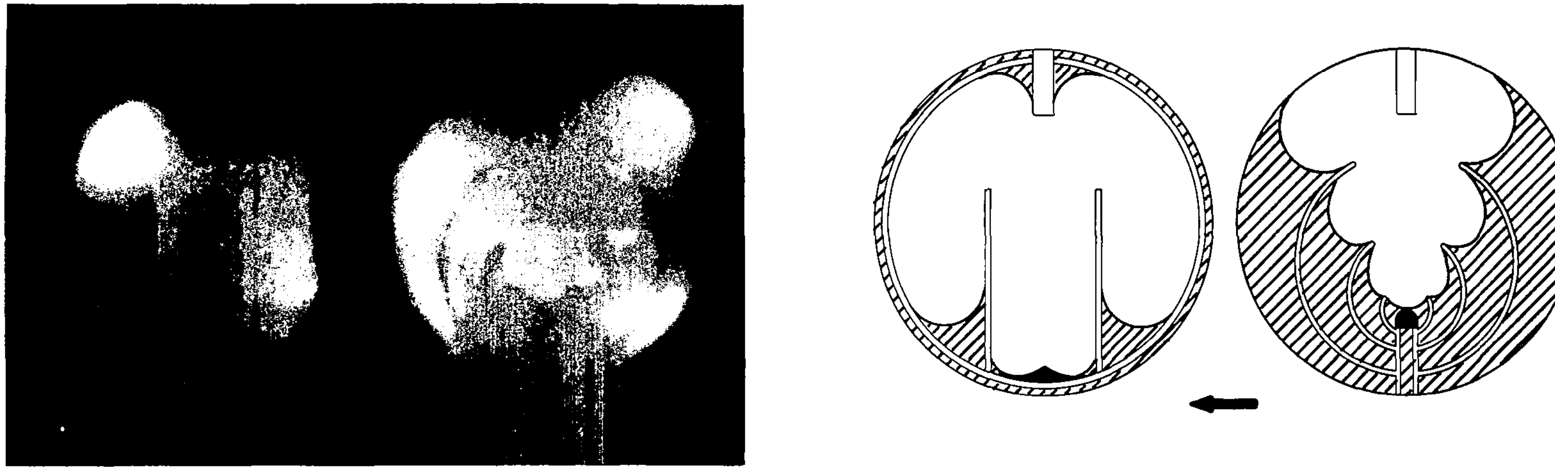


(a) Initial configuration before liquid transfer. Wall-liner in receiver tank partially filled.

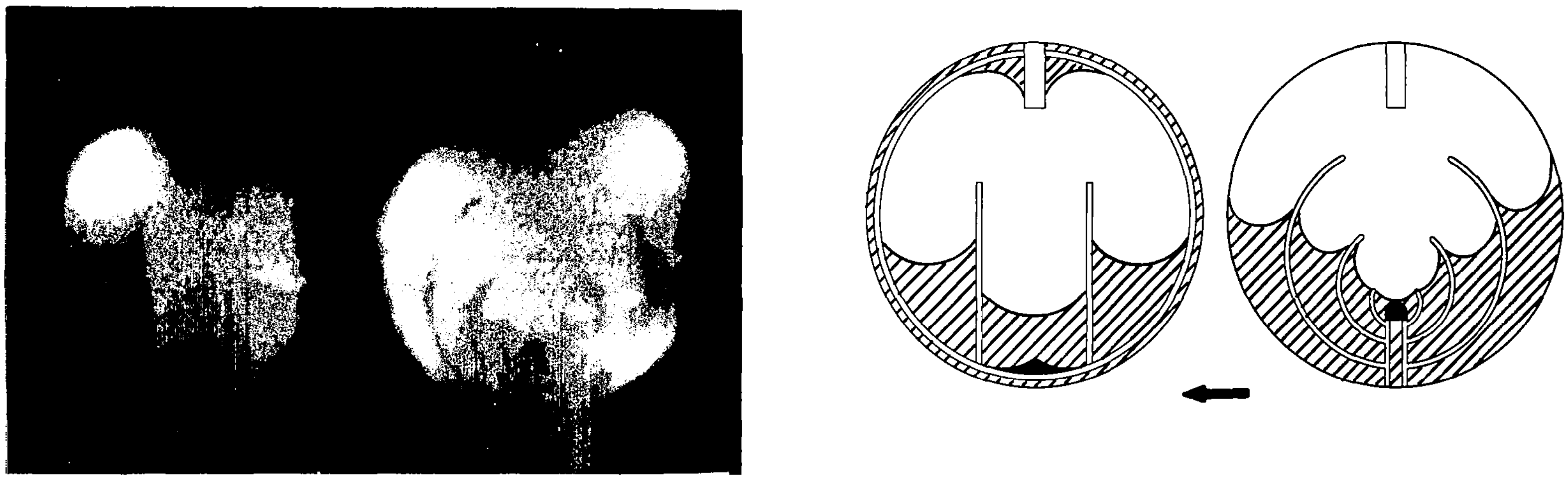


(b) Wall-liner in receiver tank completely filled; time interval, 8 seconds.

Figure 4. - Photographic sequence illustrating liquid-transfer phenomenon in baffled tanks during transearth coast. Approximate flow rate 0.83 cubic centimeters per second. Curved-web design supply tank and standpipe-liner design receiver tank.

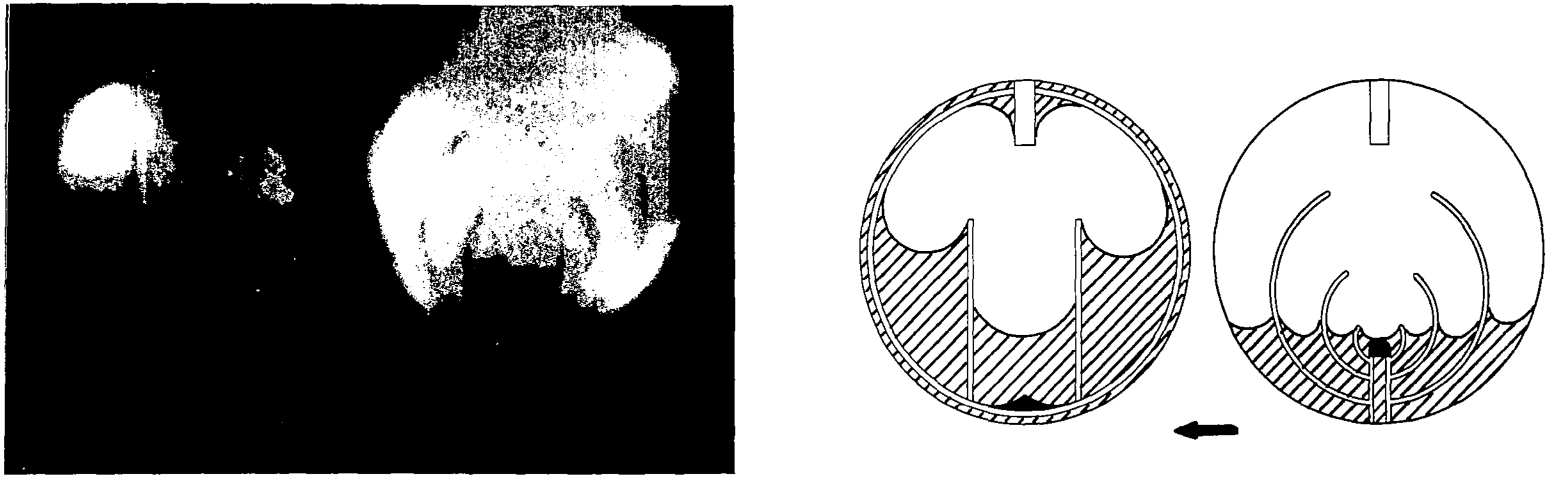


(c) Interface shapes during transfer; time interval, 12 seconds.

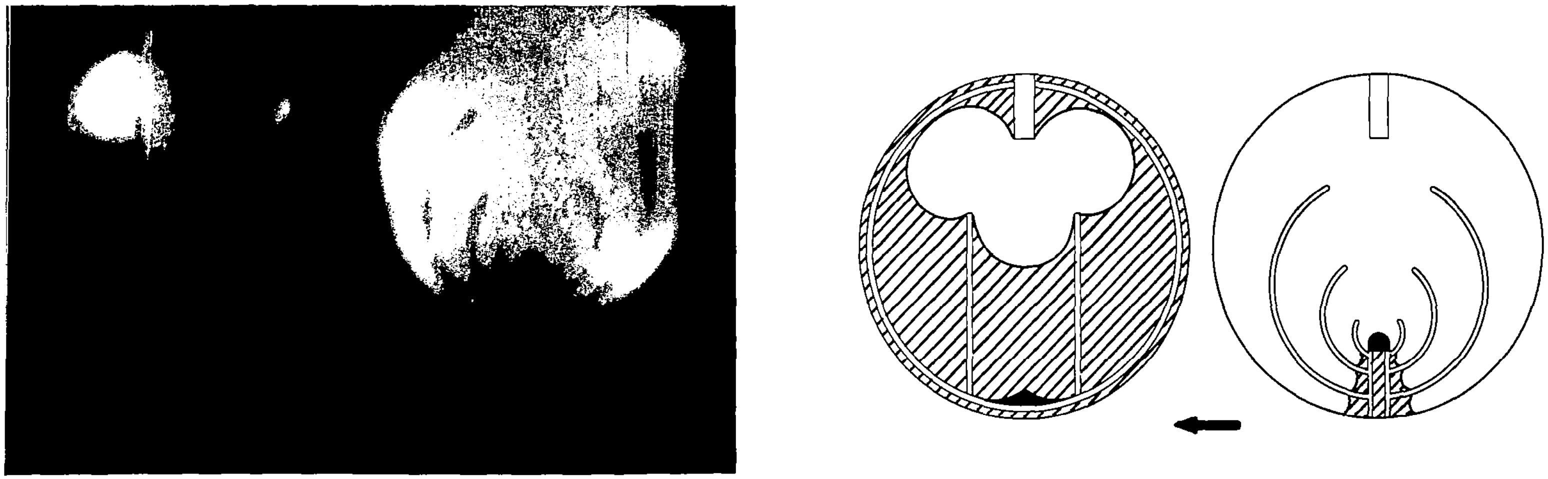


(d) Interface shapes during transfer; time interval, 20 seconds.

Figure 4. - Continued.

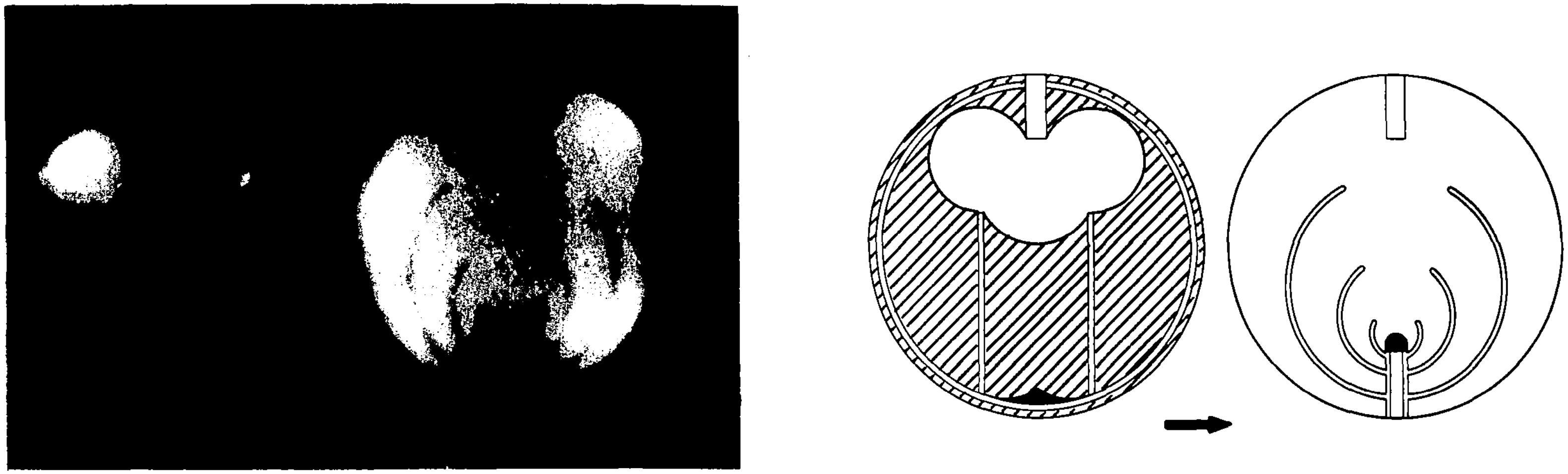


(e) Interface shapes during transfer; time interval, 26 seconds.

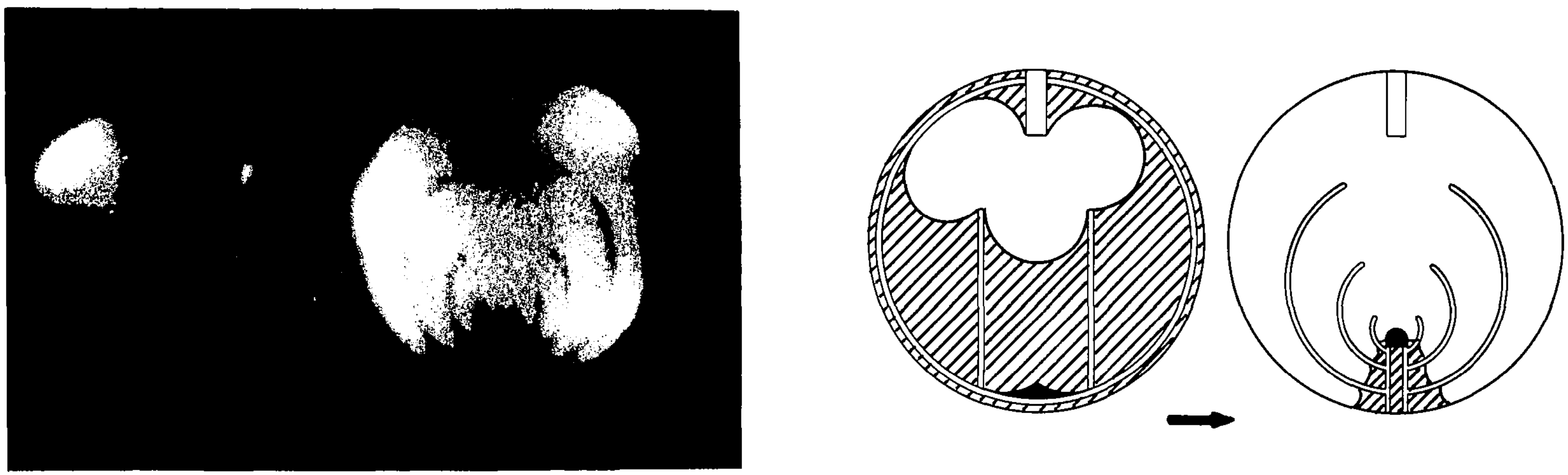


(f) Incipience of vapor ingestion in curved-web design supply tank. End of transfer; time interval, 39 seconds.

Figure 4. - Concluded.

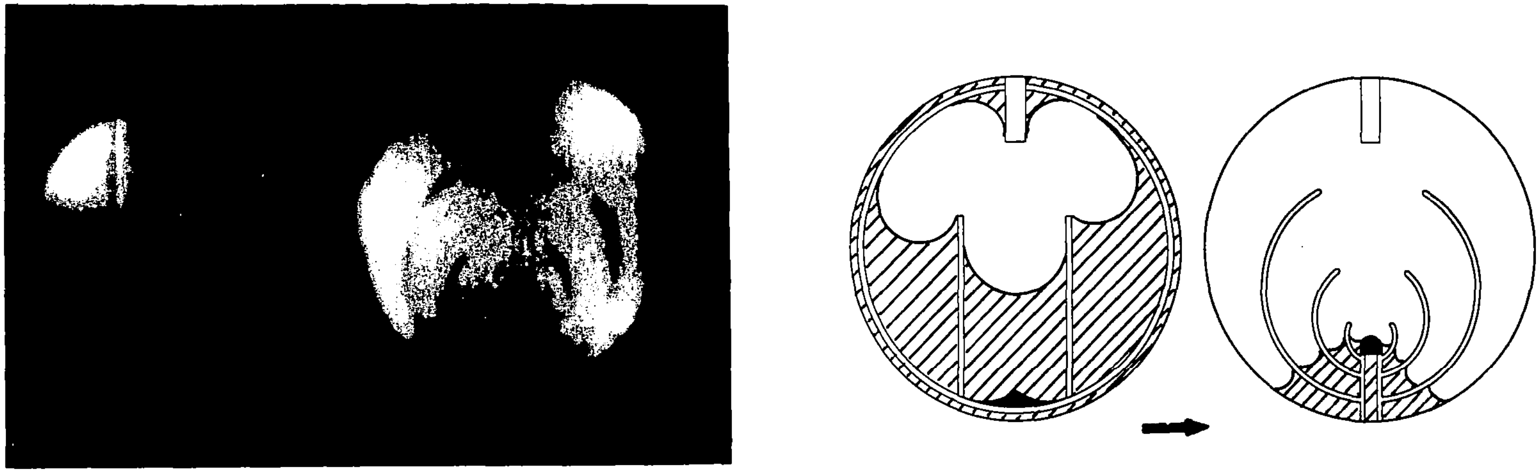


(a) Initial configuration before liquid transfer.

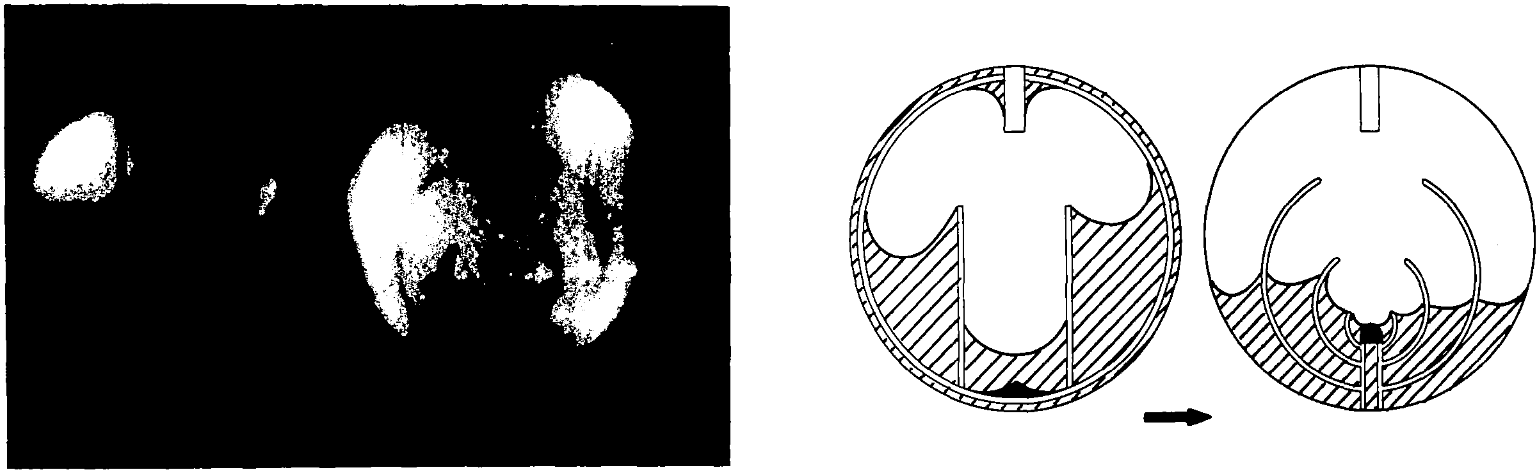


(b) Interface shapes during transfer; time interval, 4 seconds.

Figure 5. - Photographic sequence illustrating liquid transfer phenomenon in baffled tanks during transearth coast. Approximate flow rate 0.67 cubic centimeters per second. Standpipe-liner design supply tank and curved-web design receiver tank.

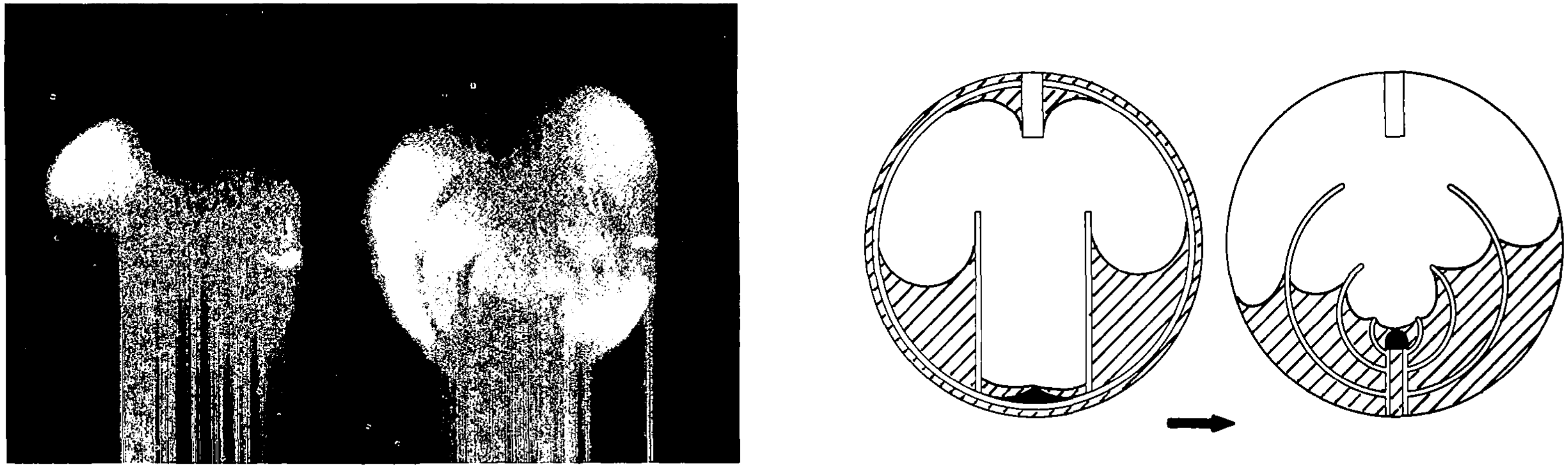


(c) Interface shapes during transfer; time interval, 12 seconds.

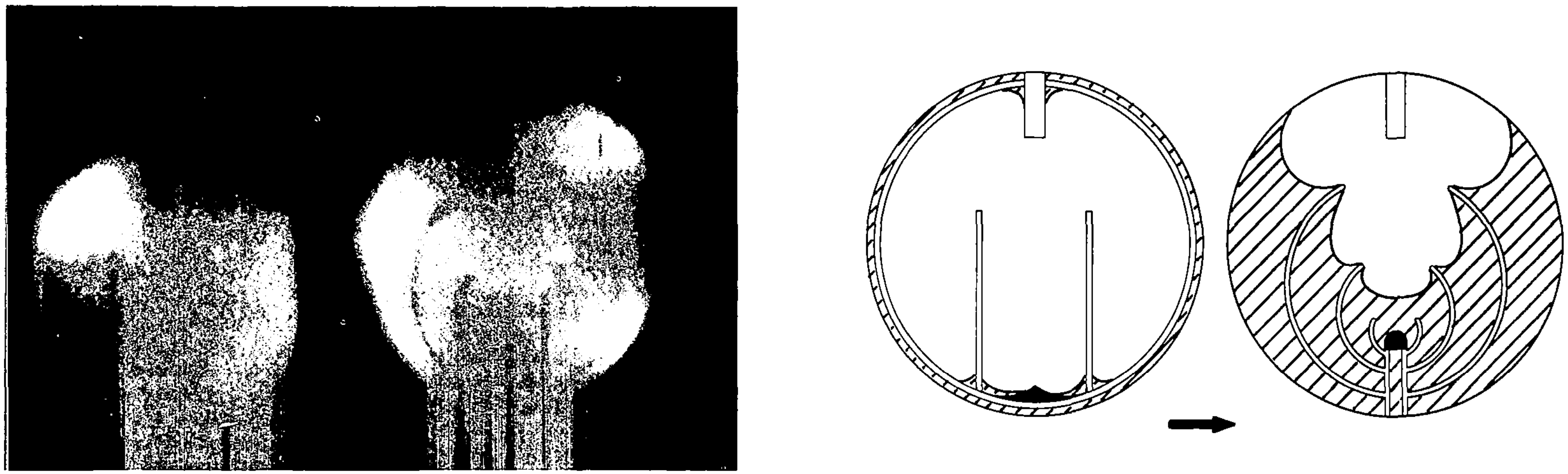


(d) Interface shapes during transfer; time interval, 21 seconds.

Figure 5. - Continued.

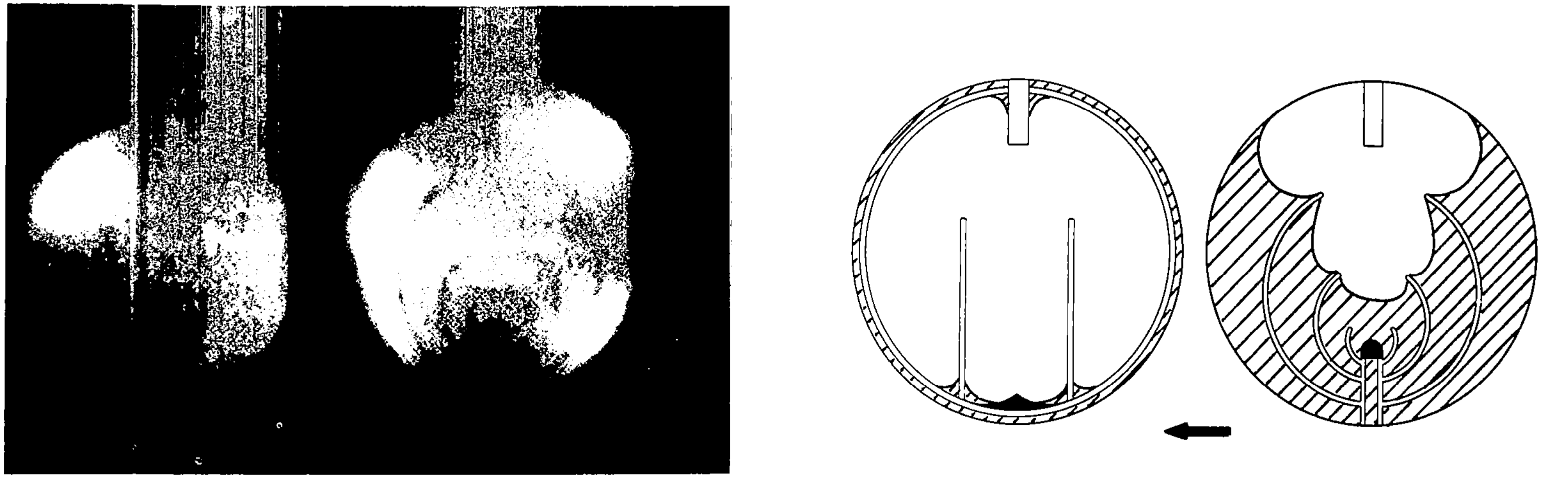


(e) Standpipe section nearly emptied; time interval, 29 seconds.

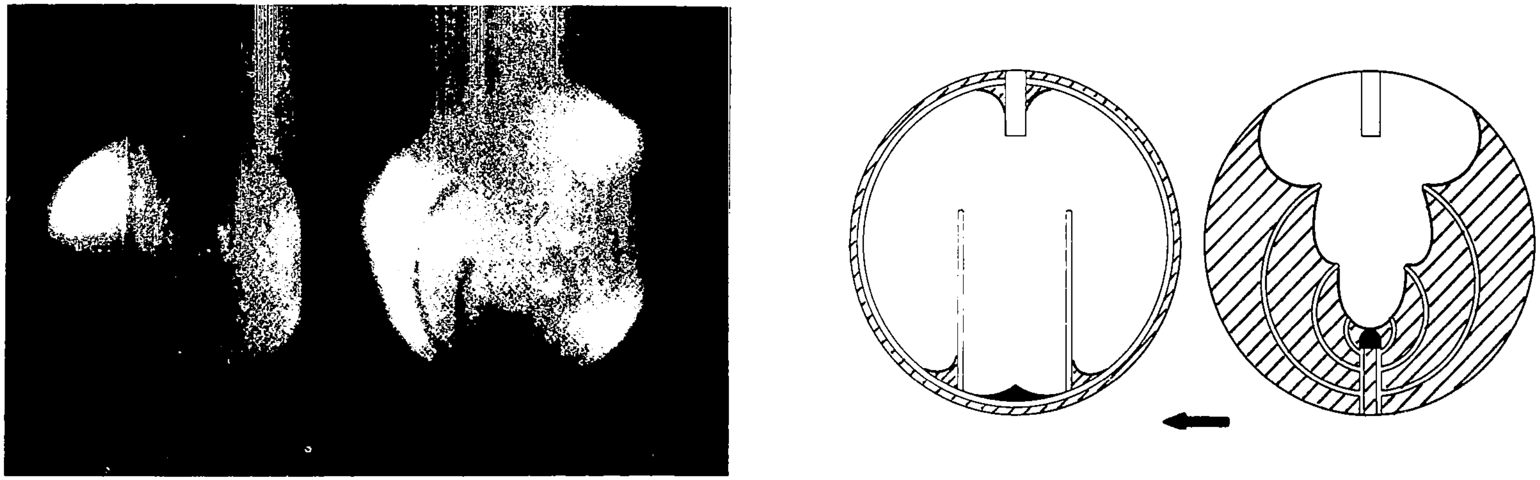


(f) Standpipe-liner supply tank emptied with exception of wall-liner. End of transfer, time interval, 48 seconds.

Figure 5. - Concluded.

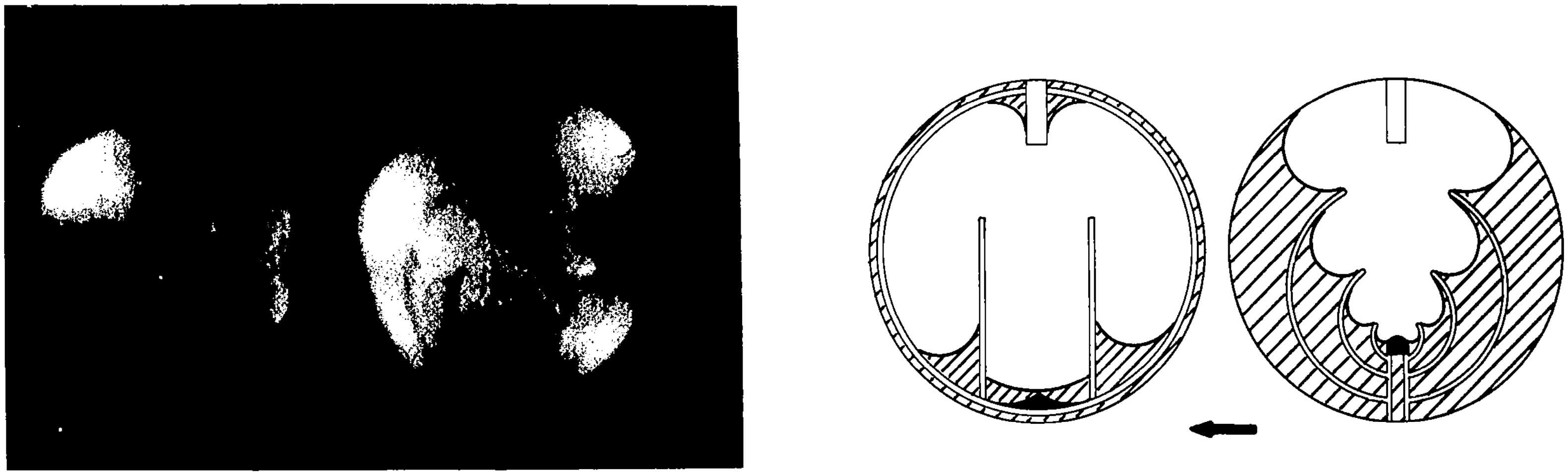


(a) Initial configuration before liquid transfer. Wall-liner in receiver tank filled.

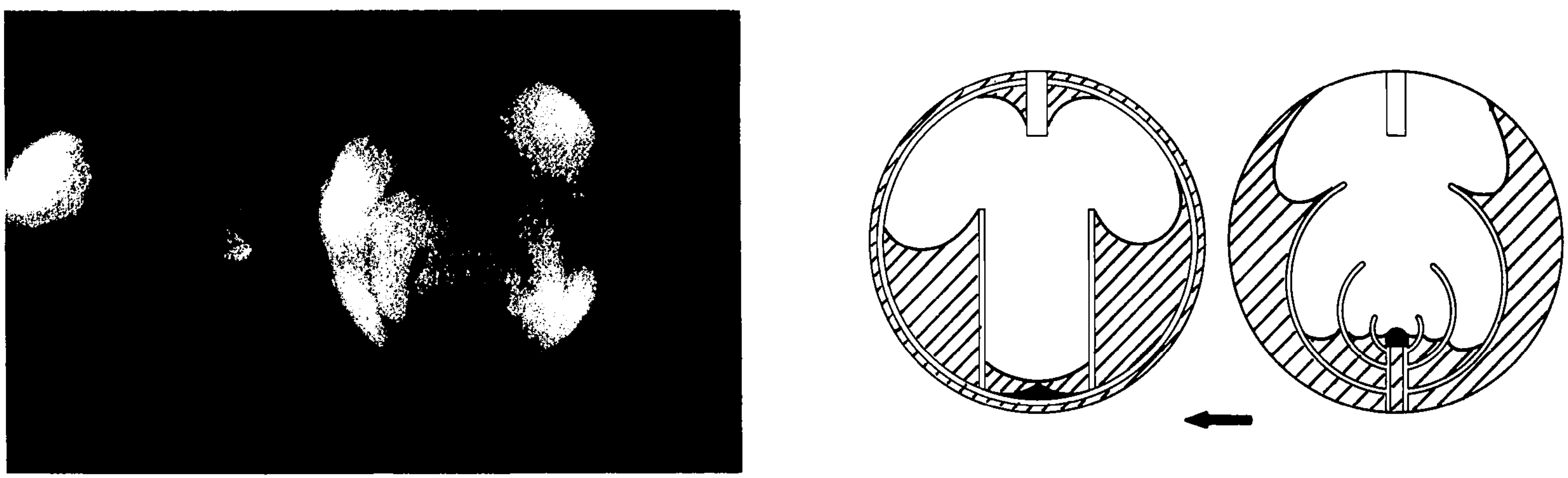


(b) Wall-liner in receiver tank completely filled; time interval, 2 seconds.

Figure 6. - Photographic sequence illustrating liquid-transfer phenomenon in baffled tanks during transearth coast. Approximate flow rate 3.5 cubic centimeters per second. Curved-web design supply tank and standpipe-liner design receiver tank.

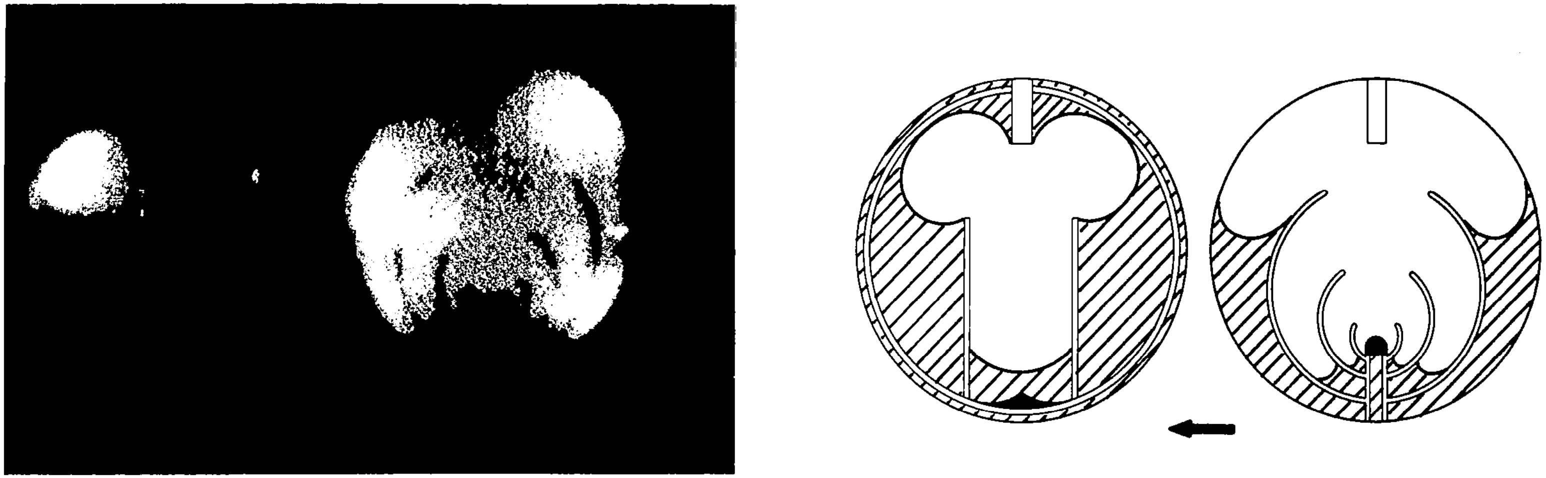


(c) Interface shapes during transfer; time interval, 4 seconds.

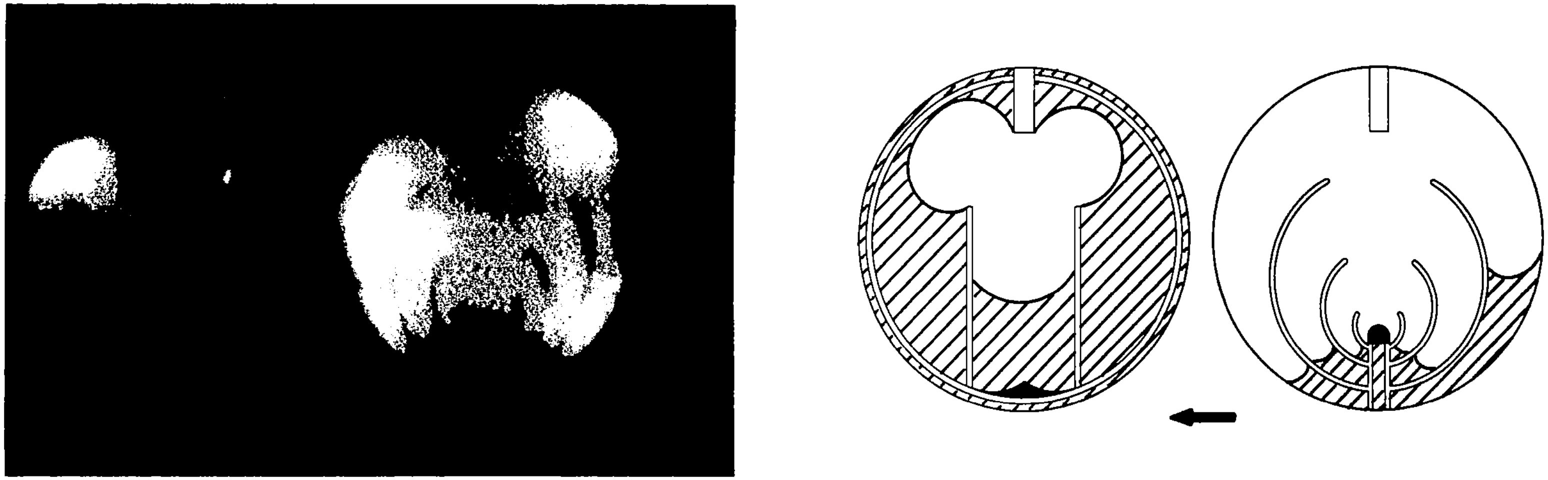


(d) Interface shapes during transfer; time interval, 6 seconds.

Figure 6. - Continued.

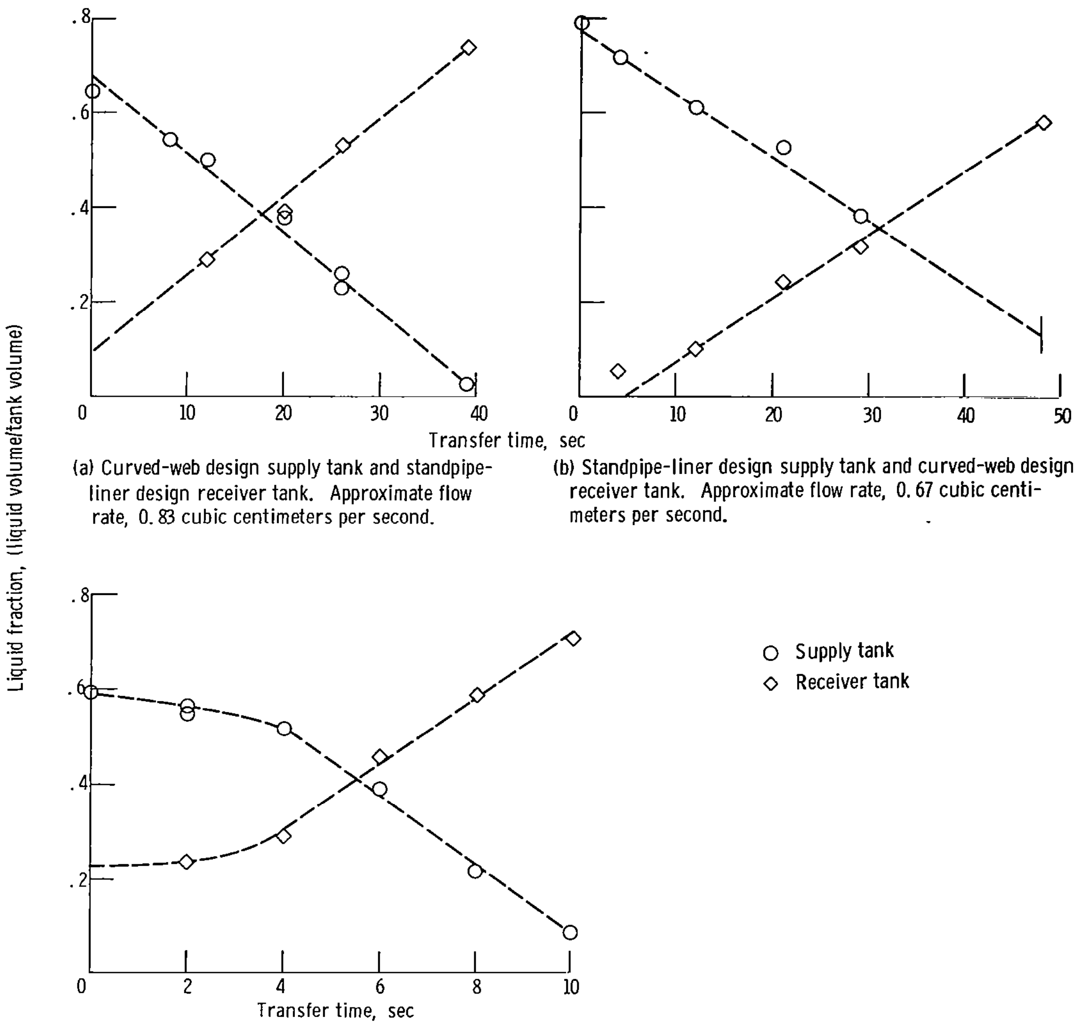


(e) Interface shapes during transfer; time interval, 8 seconds.



(f) Incipience of vapor ingestion in curved-web design supply tank. End of transfer; time interval, 10 seconds.

Figure 6. - Concluded.



(a) Curved-web design supply tank and standpipe-liner design receiver tank. Approximate flow rate, 0.83 cubic centimeters per second.

(b) Standpipe-liner design supply tank and curved-web design receiver tank. Approximate flow rate, 0.67 cubic centimeters per second.

(c) Curved-web design supply tank and standpipe-liner design receiver tank. Approximate flow rate, 3.5 cubic centimeters per second.

Figure 7. - Estimated liquid fractions during transfer.

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